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Parameter Sensitivity of a Surface Water Quality Model of the Lower South Saskatchewan River—Comparison Between Ice-On and Ice-Off Periods

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Abstract Little is known about seasonal differences (ice-on vs. ice-off periods) and the sensitivity of in-stream processes to surface water quality constituents in rivers that have a persistent ice cover in winter. The goal of this study is to investigate the sensitivity of nutrient transformation processes on surface water quality, especially rivers in cold regions where ice-covered conditions persist for a substantial part of the year. We established a sensitivity analysis framework for water quality modelling and monitoring of rivers in cold regions using the Water Quality Analysis Program WASP7. The lower South Saskatchewan River in the interior of western Canada, from the Gardiner Dam at Lake Diefenbaker to the confluence of the North and South Saskatchewan rivers, is used as a test case for this purpose. The study reveals that parameter sensitivities differ between ice-covered and ice-free periods and biological model parameters related to nutrient-phytoplankton dynamics can still be sensitive during the ice-covered season. For example, sediment oxygen demand is an important parameter during the ice-on period, whereas parameters related to nitrification are more sensitive in the ice-off period. These results provide insight into important water quality monitoring aspects in cold regions during different seasons.

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1 Introduction

Population growth, land use alteration and climate change all contribute to the eutrophication of surface waters leading to aquatic ecological stress and threats to animal and human health [1]. Water quality issues are particularly pressing for regions having intense economic development and extensive land modifications. Water quality studies can help to better identify, manage and mitigate eutrophication impacts. As a dynamic and complex system containing key features of global water resources, the Saskatchewan River Basin is an exemplar for investigating contemporary water challenges [2]. This paper focuses on the water quality of the lower South Saskatchewan River (LSSR) in the interior of western Canada. Despite some water quality studies related to agricultural activities and flow change of the upper South Saskatchewan River (USSR) (e.g. [3, 4]), the LSSR has received little attention in the literature. The LSSR receives water from the Gardiner Dam at Lake Diefenbaker, which heavily modifies the seasonal flows from the Canadian Rocky Mountains in Alberta, and flows northward to the confluence of the North and South Saskatchewan rivers. It is an important source of drinking water, is used as a receptacle for treated wastewater and storm water (e.g. in the city of Saskatoon) and also receives discharges from sewage lagoons all along the river course.

Due to the trapping effect of substances in the Lake Diefenbaker reservoir, the LSSR has a better water quality than the USSR, which receives substantial inputs of nutrients from urban and agricultural sources in upstream Alberta. However, nutrient concentrations are still high enough that there is still a moderate risk of negative impacts to the river stretch's water quality [5]. This risk could increase due to the increasing eutrophication of Lake Diefenbaker, potentially leading to larger nutrient loadings to the LSSR in the future. Hence, it is important to quantify the water quality of the river stretch, determine

the key processes maintaining its current ecological state and identify sources of nutrient loadings to the LSSR.

Water quality models are important tools for quantifying water quality conditions of surface waters and for providing a framework to explore water management options and the effects of climate change on aquatic ecosystems. Several studies have discussed the effect of ice-covered conditions on dissolved oxygen concentrations, for example [6–8]. The presence of an ice cover significantly affects both hydrological and chemical regimes of the river [8]. For instance, ice covers reduce the reaeration rate, which subsequently reduces dissolved oxygen (DO) concentrations in the water column [8]. However, little is known about eutrophication under ice conditions. Weyhenmeyer et al. [9] compared water quality of lakes after ice-covered winters and ice-free winters. Higher chlorophyll concentrations were observed after ice-free winters than ice-covered winters. Since the LSSR is covered by ice for at least one third of the year (on average 127 days), it is imperative that the water quality model applied to this river stretch have components that represent under-ice conditions. The Water Quality Analysis Simulation Program (WASP7) [10, 11] is a suitable model for this purpose.

The objective of this paper is to study the sensitivity of several parameters to model outputs for two seasons, ice-covered season and ice-free season, using WASP7. Sensitivity analysis can be an effective tool for identifying the most influential parameters in model simulations [12–14]. Similar sensitivity studies have been carried out in the past using WASP to determine, for example, (i) the most crucial processes causing DO depletion in floodwaters diverted to off-channel storage facilities [15] and (ii) the most sensitive processes in transporting and retaining heavy metal contaminants on flooded agricultural lands [16]. The results from this water quality sensitivity study are expected to provide valuable information for a monitoring scheme design, which would capture the changes in surface water quality in the South Saskatchewan River. Moreover, this study provides an exemplar for investigating the importance of model parameters in regions having extended ice-covered periods. The following sections provide details of the study area and model set-up. Model outputs, sensitivity analysis results and a discussion of the implications of different parameter sensitivities in the ice-covered and ice-free models are given before the final concluding section related to sensitive seasonal water quality processes.

2 Study Area

The South Saskatchewan River (SSR) is a major river in Canada, located in the provinces of Alberta and Saskatchewan. The lower South Saskatchewan River (LSSR) conveys water from the Gardiner Dam at Lake

Diefenbaker to the Saskatchewan River. The LSSR is approximately 330 km long and receives large lagoon effluents from the towns of Outlook, Martensville, Warman and Osler as well as treated effluent from the Saskatoon wastewater treatment plant. Outfalls from smaller community lagoons are dotted along the river stretch as well. Figure 1 shows a map of the study area and the location of the water quality monitoring stations. The water quality data from these sampling sites were provided by Saskatchewan's Ministry of Environment. The sampled values were used for model calibration, validation and sensitivity analyses.

There are four gauging stations along the LSSR; however, only one station has historical daily flows for our 3-year study period 2007–2009. To evaluate the consistency of the flows in the river, historical monthly flow rates available at two gauging stations, Saskatoon and St. Louis, are superimposed in Fig. 2, which indicated that flow remains almost constant from Saskatoon to St. Louis. Also, there are no major tributaries along the LSSR and, for modelling purposes, it was reasonable to assume that the flows are relatively the same along this river stretch. Figure 3 shows the monthly flow statistics from 1970 to 2012 of the Water Survey of Canada (WSC) station, the SSR at Saskatoon (Station no. 05HG001). The freshet peak is usually dampened by Lake Diefenbaker's storage uptake. High-flow events usually occur in summer, from May to August, following snowmelt in the Rocky Mountains. For this period of record, the maximum discharge values occurred in June 1975 and July 2011. In winter, the average flow is around 250 cms.

The B values in the historical flow data reported by Environment Canada provide an indication when the flow is influenced by the presence of the ice cover in the river. As shown in Fig. 4, ice cover formation over the past 100 years appears to follow a trend to later freeze-up dates. A rank trend test based on Mann [17] and Kendall [18] was used for detecting a possible linear monotonic trend over many years. The slope of the linear trend line was estimated using a nonparametric method proposed by Sen [19]. Although the ice-on time series has a very weak autocorrelation (0.07), the significance of the trend slope does not differ significantly with or without autocorrelation adjustment (see [20] for details of the autocorrelation adjustment). The change in ice cover formation for the SSR gauging station at Saskatoon is around 2 days per decade (p value = 0.001). A clear trend is not distinguishable for the ice breakup dates. Therefore, understanding parameter sensitivity under ice was motivated.

3 Model Description

The Water Quality Analysis Simulation Program (WASP7) is an enhanced Windows version of the original WASP program [21, 22, 10]. WASP7 has a user-friendly interface allowing

Fig. 1 Map of the lower South
Saskatchewan River
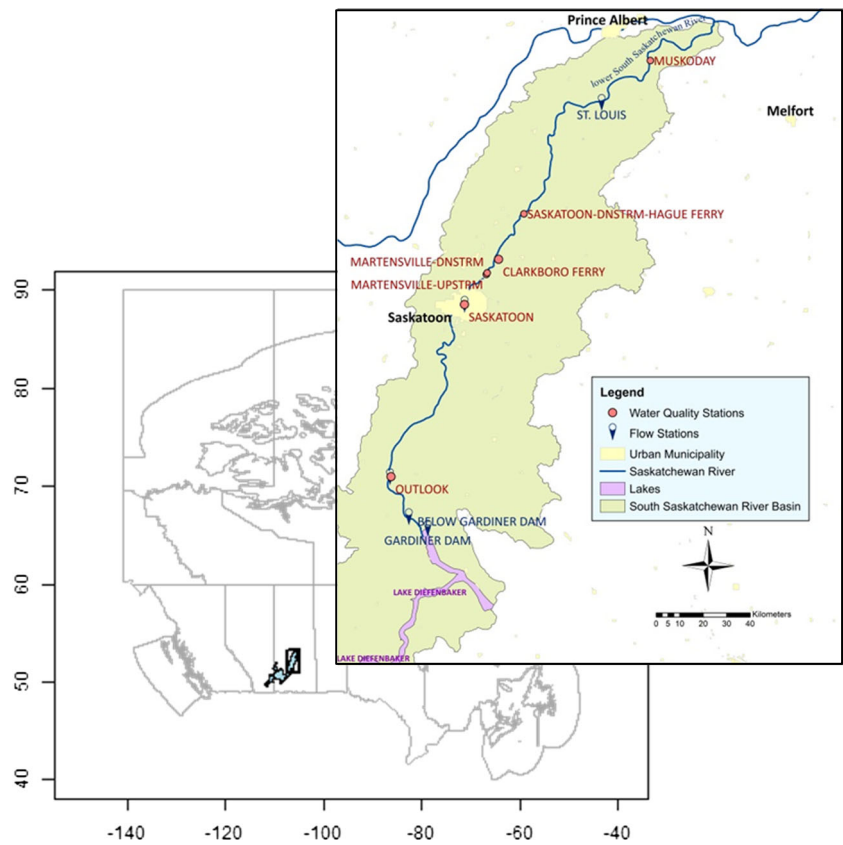
users to define time-variable boundaries, loads, advection flows and other parameters via a graphical user interface (GUI). The model predicts spatial and temporal water quality based on a series of mass balance equations in one, two or three dimensions. The model can be discretised vertically throughout the water column and bottom sediments and horizontally to capture lateral and longitudinal variations of water quality constituents. One of the advantages of the model is that it can be linked to a hydrodynamic model that simulates

dynamic river flows. The WASP model has been widely used to study water quality of many surface waters and various applications [23–25] and can be easily implemented to study the effect of climate change, population growth and agricultural and industrial intensification on surface water quality.

In this study, a 1-D approach with variations simulated in the longitudinal direction was implemented to simulate water quality along the LSSR. EUTRO, a module in WASP7 specifically focused on eutrophication processes, simulates
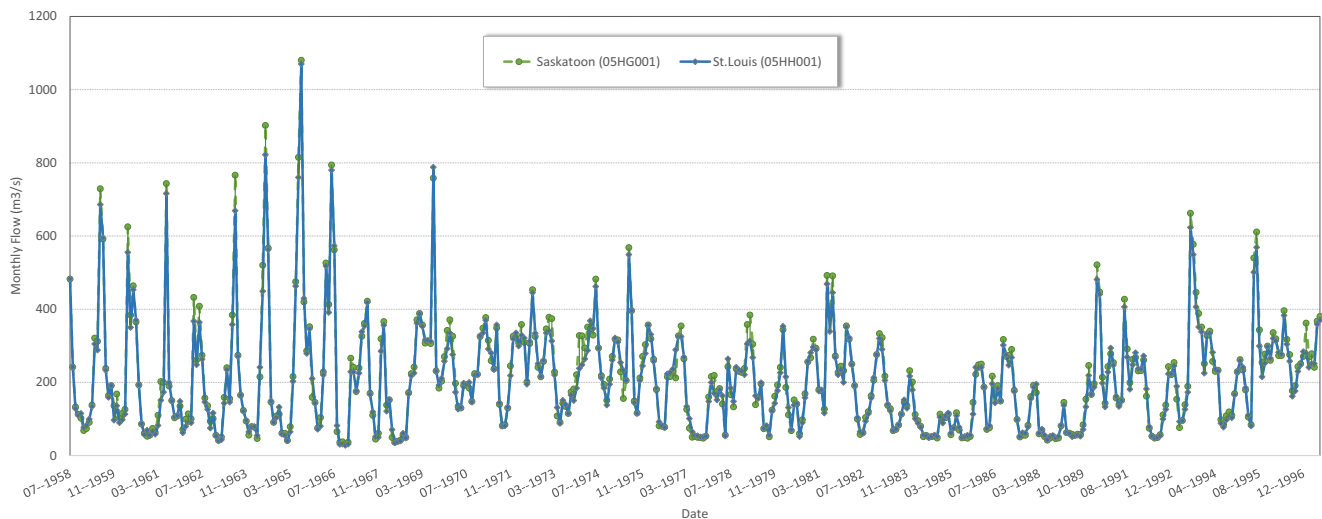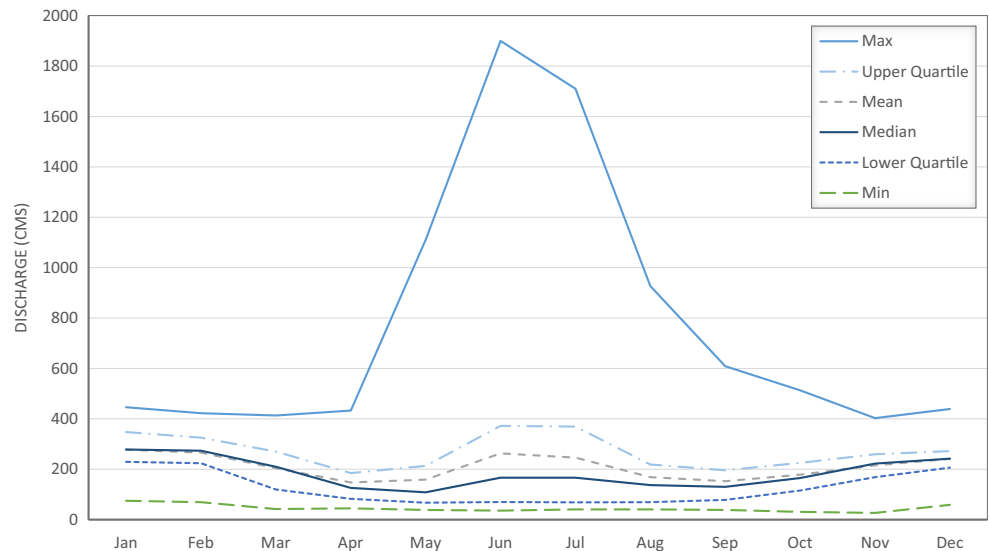

Fig. 2 Historical monthly flow rates at the Saskatoon and St. Louis gauging stations

Fig. 3 Monthly statistics of discharge recorded at the South Saskatchewan River WSC station from 1970 to 2012

phytoplankton, dissolved oxygen (DO) and nutrient dynamics with the option of using six different levels of increasing complexity, reflecting the amount of data available for model calibration. In this study, an intermediate level was used to simulate DO concentrations in the water column based on the growth and nutrient and light limitation dynamics of phytoplankton.

4 Model Set-up

4.1 Discretisation

The LSSR is approximately 330 km in length. The river was discretised into 673 segments, each 500 m long. One hundred

eighty-seven surveyed cross-sectional profiles extracted from a Hydrologic Engineering Center River Analysis System (HEC-RAS) model (provided by the Saskatchewan Water Security Agency) were available at different locations along the river. The cross-sectional profiles for each segment were interpolated from the surveyed HEC-RAS cross sections. The resolution is fine enough to capture the morphometric variations along the river. The HEC-RAS model was used to estimate the initial hydrodynamic data required for the WASP7 model. At each time step, volumes are changed to maintain flow continuity.

Daily flow rates were available from the Environment Canada website and were used for the simulation. Since there were no major tributaries along the river, the flow rate remained constant along the river in the model. Therefore,

Fig. 4 Dates of ice-in (**a**) and ice-out (**b**) at the South Saskatchewan River gauging station at Saskatoon
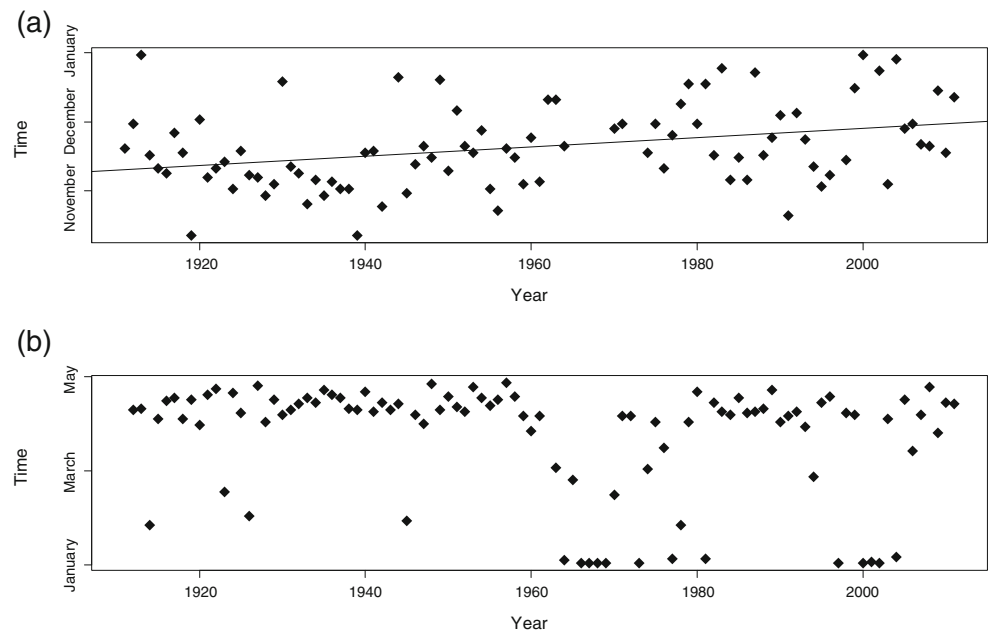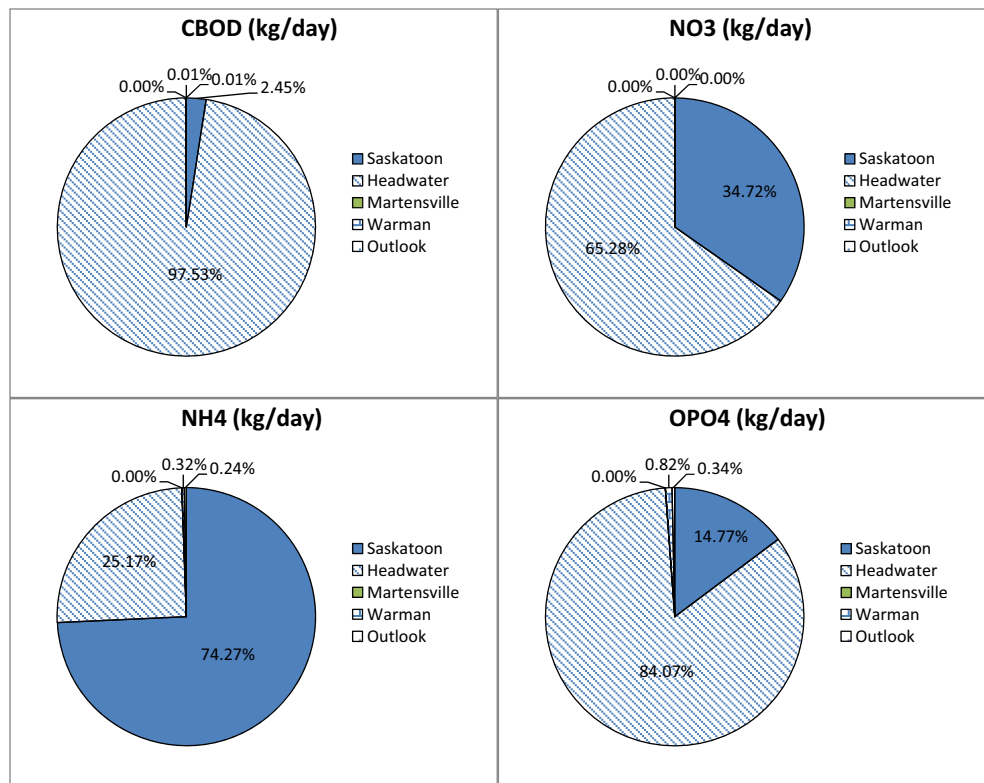
Fig. 5 Estimated overall nutrient
and carbonaceous load
contributions to the LSSR

daily flows reported at the Saskatoon gauge were applied to the model simulations. The hydrodynamic data including depths, widths, velocities and volumes were calculated from the HEC-RAS model based on the annual mean flow. One-dimensional kinematic wave in WASP7 was selected, which calculates flow wave propagation with resulting variations in flows, volumes, depths and velocities throughout the stream network. Flow is primarily controlled by bottom slope and roughness.

4.2 Loading and Boundary Conditions

The river receives the municipal effluents from Saskatoon, Outlook, Martensville, Warman and Osler. The loading data were obtained from the Water Security Agency and the City of Saskatoon Wastewater Treatment Plant. Daily loads from the Saskatoon wastewater treatment plant were considered in this study. Martensville continually discharges its lagoon sewage during the summer months. Warman, on the other hand, only discharges in the spring and fall. Osler has emergency discharges to the river; however, no discharge was reported from 2007 to 2009. The town of Outlook discharges their lagoon twice per year (spring and fall) for a total of 7 days. The loading from this lagoon was less than 0.2% of the loading from the upstream river reach; therefore, we did not include the loading from this lagoon. Figure 5 shows the nutrient load estimates to the river from the start of the LSSR and the river

stretch's point sources. The main contribution of the load sources is from the upstream boundary condition and Saskatoon's wastewater treatment plant (WWTP). The contributions of loads from Martinsville and Warman increase during their lagoon discharge seasons (as shown in Fig. 6).

It should be noted that the model assumes immediate and complete mixing of a point source loading upon entering the river. In reality, complete mixing does not occur until some distance downstream from the point of entry [26], which should be taken into account when comparing simulated results with concentrations sampled downstream of a point source.
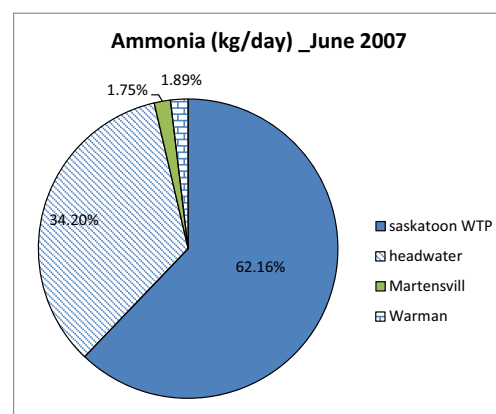

Fig. 6 Estimated ammonia load contributions to the ISSR in June 2007

The boundary segments include the most upstream and the most downstream segments of the river. The measured concentrations at the closest sampling stations to these segments were used as boundary concentrations. Lateral boundaries were not included because, as mentioned previously, there are no major tributary inflows emptying into the LSSR.

4.3 Functions

WASP7 allows users to specify time-variable functions as input which include, for this study, daily time-variable functions for water temperature, light extinction, fraction of light, solar radiation, ice-covered periods and reaeration. Since time-varying water temperature was available at water quality stations along the LSSR (see Fig. 7), water temperature was considered in the simulation exercise and was used as the input function. Similarly, ice-cover fractions (0 or 1) were used as the input function and were estimated based on the *B* values in the flow data recorded by Environment Canada at the SSR gauge in Saskatoon. Light extinction was calculated from Secchi depth measurements as suggested in the literature [27, 28]. The monthly average Secchi depth for Lake Diefenbaker (based on SEEMS data) was 5 m in winter and ranged from 3 to 6 m in summer. Figure 7 shows daily fraction of light, which was obtained from the http://www.timeanddate.com website and daily solar radiation that was

extracted from NCEP reanalysis data provided by the NOAA/OAR/ESRL website at http://www.esrl.noaa.gov/psd/. Reaeration rates for open-water conditions were estimated using the reaeration formulas, O'Connor-Dobbins, Churchill and Owen-Gibbs, provided graphically in Chapra [29]. These rates reduce to zero during ice-covered conditions.

4.4 Initial Conditions

The initial concentrations in the model stem from averaged measured concentrations of nutrients along the river. The initial concentrations for the segments were linearly interpolated from the averaged measured concentrations sampled at the water quality monitoring stations. Organic nitrogen (ON) and organic phosphorus (OP) were not available in the database. ON was calculated as total Kjeldahk nitrogen (TKN) minus ammonium (NH_4), and similarly, OP was calculated as total phosphorus (TP) minus ortho-phosphate (OPO_4), as suggested by Tufford and McKellar [30].

5 Sensitivity Analysis

A local sensitivity analysis was carried out to evaluate the effect of each parameter on the model outputs. Although local sensitivity analyses may not account for the sensitivities in

Fig. 7 **a** Measured water temperature. **b** Daily measured solar radiation and fraction of daylight
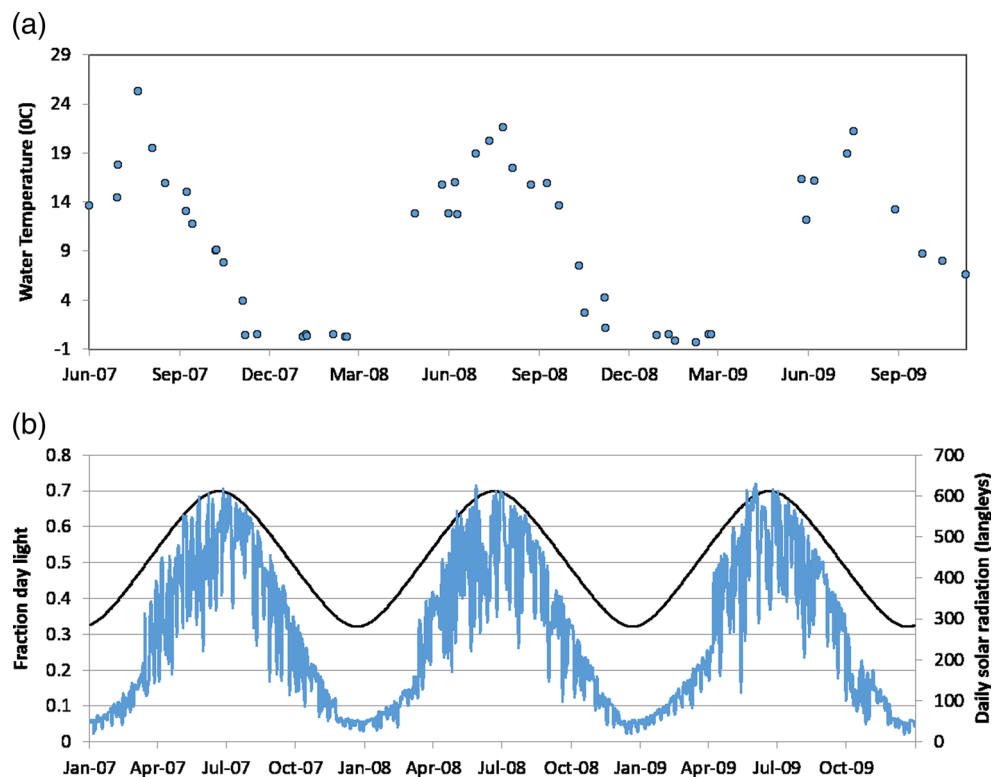
Table 1 Parameters and the values used for the simulation

Parameter	Parameter description	Value	Unit
K12C	Nitrification rate at 20 °C	2	1/day
K12T	Nitrification temperature coefficient	1.045	–
K20C	Denitrification rate at 20 °C	0.01	1/day
K20T	Denitrification temperature coefficient	1.01	–
K1C	Phytoplankton growth rate	0.5	1/day
K1T	Phytoplankton growth temperature coefficient	1.08	–
CCHL	Carbon to chlorophyll *a* ratio	40	mg C/mg Chl *a*
K1D	Phytoplankton death rate	0.2	1/day
KMNG1	1/2 saturation for N-limitation on phytoplankton uptake	0.03	mg N/l
KMPG1	1/2 saturation for P-limitation on phytoplankton uptake	0.03	mg P/l
NCRB	Nitrogen to carbon ratio	0.1	mg N/mg C
PCRB	Phosphorus to carbon ratio	0.15	mg P/mg C
K71C	N-mineralisation rate at 20 °C	0.075	1/day
K71T	N-mineralisation temperature coefficient	1.08	–
fON	Fraction of phytoplankton death recycled to ON	0.8	–
K83C	P-mineralisation rate at 20 °C	0.22	1/day
K83T	P-mineralisation temperature coefficient	1.08	–
fOP	Fraction of phytoplankton death recycled to OP	0.8	–
SOD	Sediment oxygen demand	0.5	g/m^2/day
SODT	Sediment oxygen demand temperature coefficient	1.04	–
K2	Reaeration rate at 20 °C	1.5	1/day

parameter interactions, it is still an effective and widely used method to determine the most influential model parameters and processes [31]. The sensitivity analysis was performed by increasing each parameter by 10% while holding the other parameters constant. The sensitivity ε was then assessed using the equation in the following:

$$\varepsilon = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_x - O_{\text{base}})^2}}{\Delta P} \tag{1}$$

where O_{base} is the simulated results using the base parameter setting, O_x is the simulated results using the perturbed parameter, ΔP is the difference between base and perturbed

parameter values (10% of the base parameter), and n is the total number of grids (637 river segments multiply the number of time steps for summer or winter).

In addition to Eq. 1, relative entropy was also calculated to measure the output difference between models driven by the base and perturbed parameters. In information theory, Shannon [32] introduced entropy as an 'unpredictability' measure which could be used to determine channel capacity for efficient coding (minimum amount of bytes or bits used to represent the intended information). Information theory has been suggested for hydrological model diagnostic evaluation [33, 34]. For practical application examples, Pechlivanidis [35] used entropy as a metric for parameter identification based on flow duration curves, and Chun et al. [36]
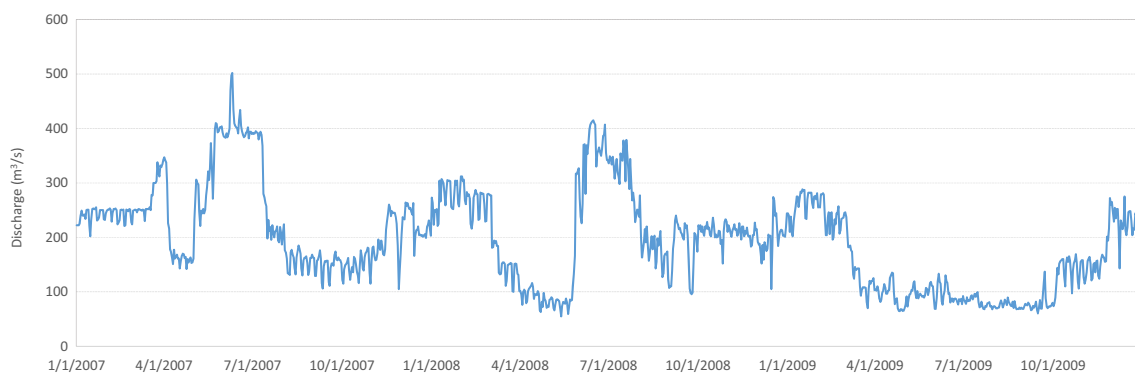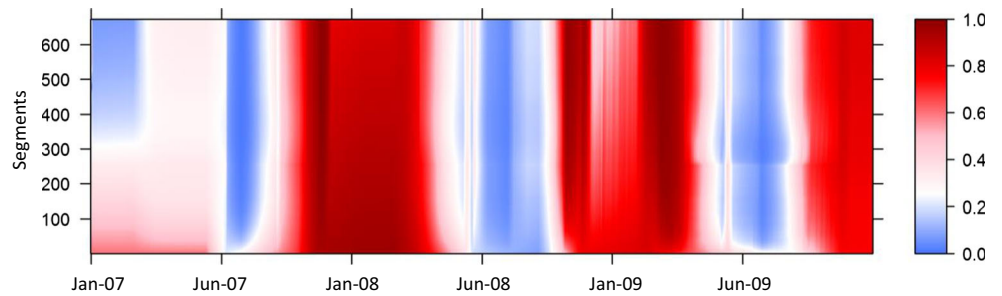

Fig. 8 Daily flow at the South Saskatchewan River WSC station between 2007 and 2009

Fig. 9 DO simulation results

demonstrated how to employ information entropy to characterise the degree of complexity of drought severity for model comparison studies.

The convex characteristic of information entropy is one of its main advantages for model diagnosis, because a strict convex response function has only one minimum [37]. Another
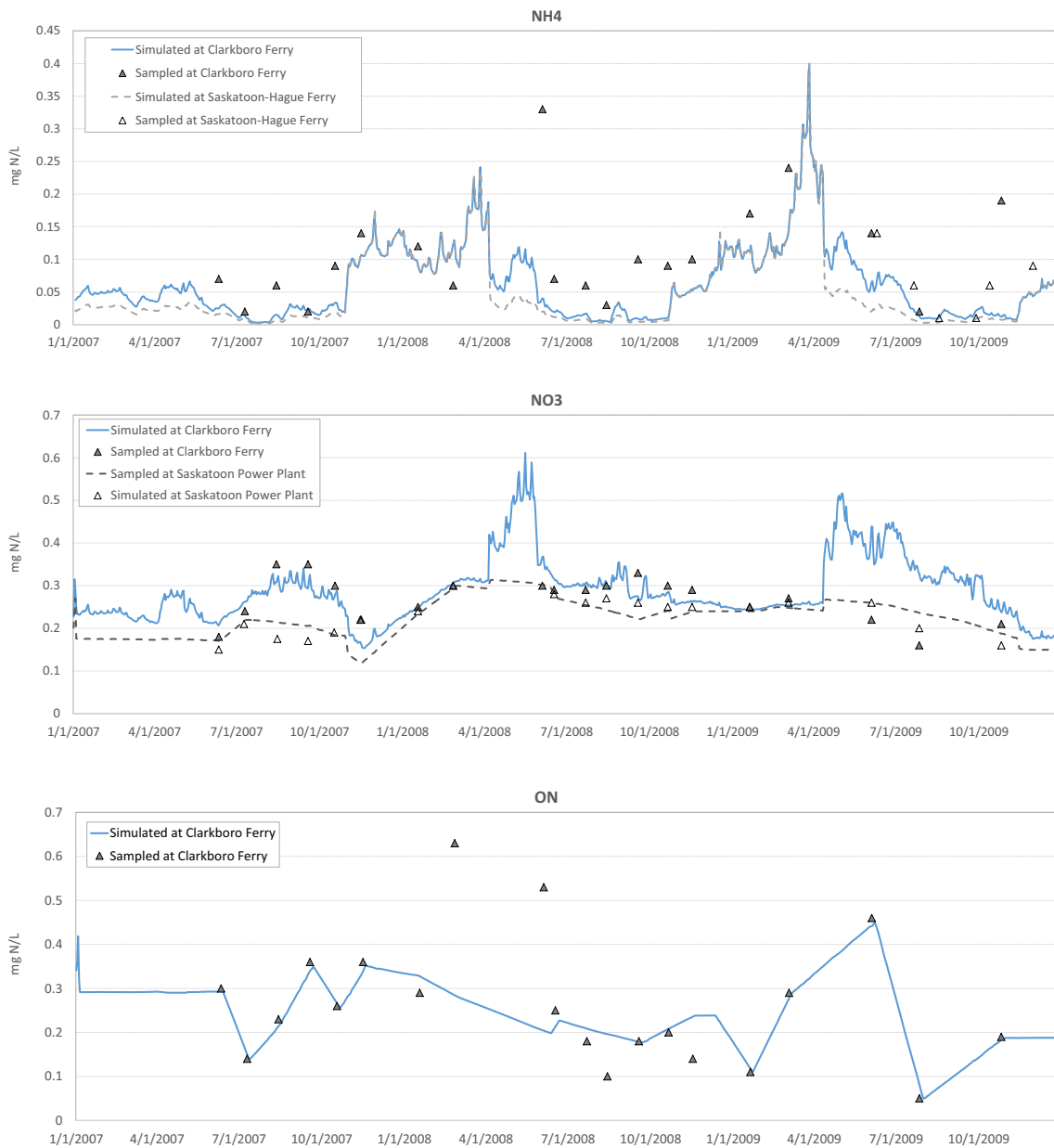

Fig. 10 Simulated versus sampled concentrations at water quality stations along the lower South Saskatchewan River between 2007 and 2009. Simulated versus sampled concentrations at water quality stations along the lower South Saskatchewan River between 2007 and 2009
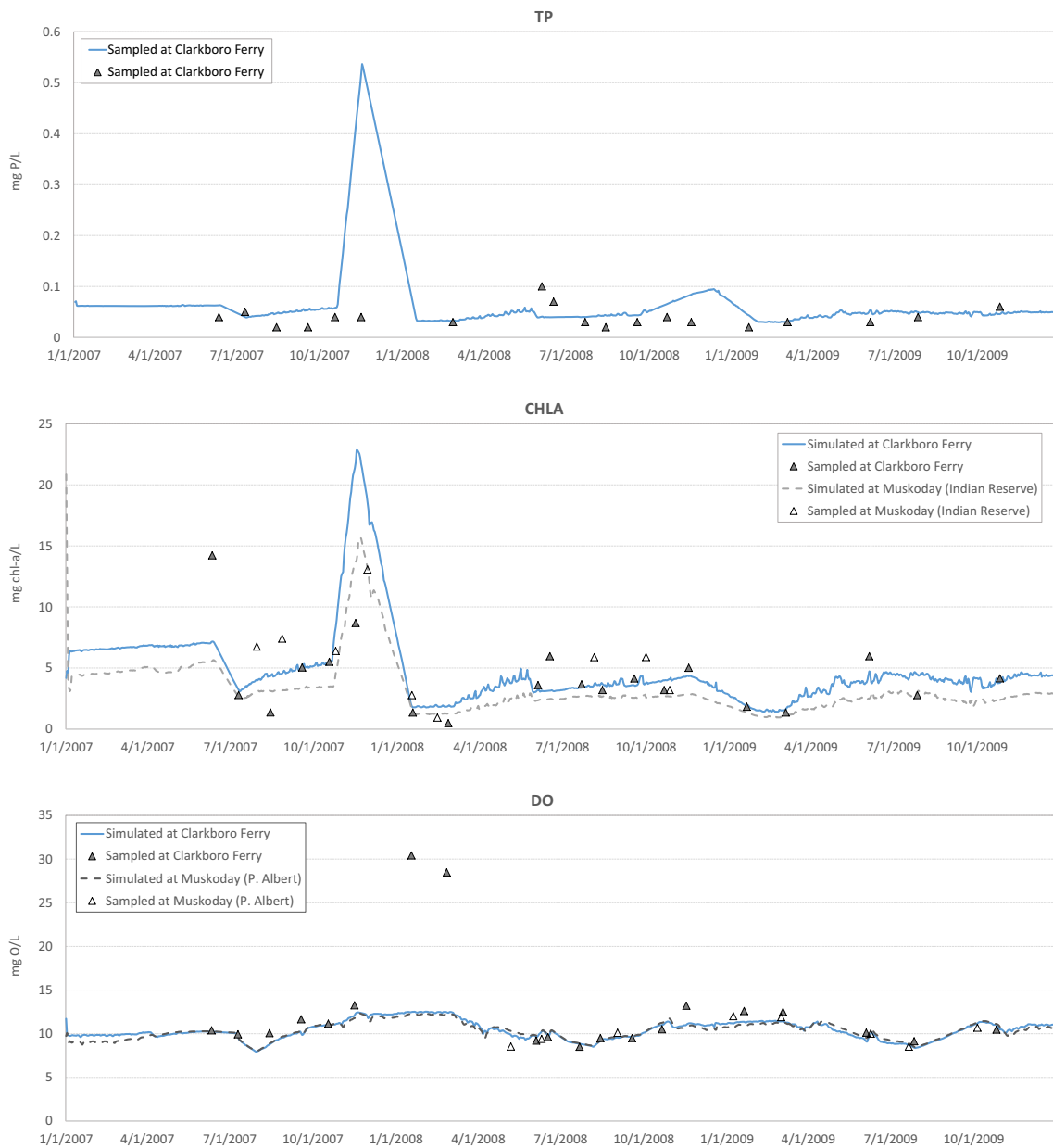
Fig. 10 (continued)

attractive property of entropy is that it is additive for independent random variables, so that the entropy of a system can be divided into parts (e.g. [38]). Using this property, relative entropy (the difference between the entropies of two systems) can be used to measure the divergence between simulated results from the base and perturbed parameters. The entropy expression is

$$H(x) = -\sum_{i=1}^{n} p(x_i)\log(p(x_i)) \tag{2}$$

where $p(x_i)$ is the probability of x_i (the simulated variables) such that the probabilities sum to 1 and n is the discretised

model output in a grid of 637 river segments by the number of time steps for summer or winter.

6 Model Results and Discussion

6.1 Simulation

Initially, the parameter values suggested in the literature or in the WASP7 manual were used for the simulation. To improve the model simulation and to best fit the simulated concentrations to the observed values, a manual trial-and-error

calibration was conducted. The water quality was simulated for the 3 years 2007 to 2009. Table 1 shows the list of the parameters and their calibrated values used for the simulation and base run of the sensitivity analyses.

Figure 8 shows the daily discharge recorded at the Saskatoon gauging station for the simulation time period. As shown in the figure, the flows in 2009 were lower compared to 2007 and 2008, especially in the summer. Typically, there is a freshet flood peak, albeit small due to the dampening effect of Lake Diefenbaker; however, no spring flooding was observed in 2009. Overall, 2009 can be considered as a low-flow year.

As an example of a baseline output from WASP7, Fig. 9 shows the simulated DO values along the river (y-axis) over the course of the 3-year simulation time (x-axis). The DO values have been normalised to scale between 0 (lowest) and 1 (highest). In general, the DO values were higher in the winter and lower in the summer. DO was relatively constant from upstream to downstream. However, in winter 2007, DO decreased in the downstream direction.

The simulation results at different water quality stations are compared to the measured data during the simulation time frame 2007 to 2009 in Fig. 10. Generally, there was a good agreement between simulated and sampled concentrations. The model overestimated nitrate in 2009 at the Clarkboro Ferry station. In November 2007, WASP7 overestimated total

phosphorous and chlorophyll a concentration peaks, which is less evident in the sampled chlorophyll a concentrations and not evident at all in the sampled TP concentrations. The high simulated chlorophyll a value originated from the upper boundary condition, which reflected the presence of an algal bloom that was observed in the Qu'Appelle Arm of Lake Diefenbaker in October 2007 (Hayden Yip, University of Saskatchewan, personal communication). Unfortunately, chlorophyll a concentrations were not sampled.

Abnormally high DO concentrations were sampled in 2008, ranging from 23 to 32 mg/l at Outlook and Clarkboro Ferry. Since chlorophyll a concentrations were very low at these sites, DO supersaturation conditions could be discounted; hence, these values were deemed to be erroneous. DO saturation values were calculated and set as the upper boundary condition for that year instead of the measured DO values. Generally, the model simulated DO concentrations very well, except for the time period when supersaturated DO values were reported.

The model performance was also assessed spatially. The average DO and NH_4 concentrations along the river (all 637 segments) were compared to the observations in Fig. 11. The area enclosed by the upper and lower lines represents 68% of the simulation results around the average values (mean ± standard deviation). The measured data during the
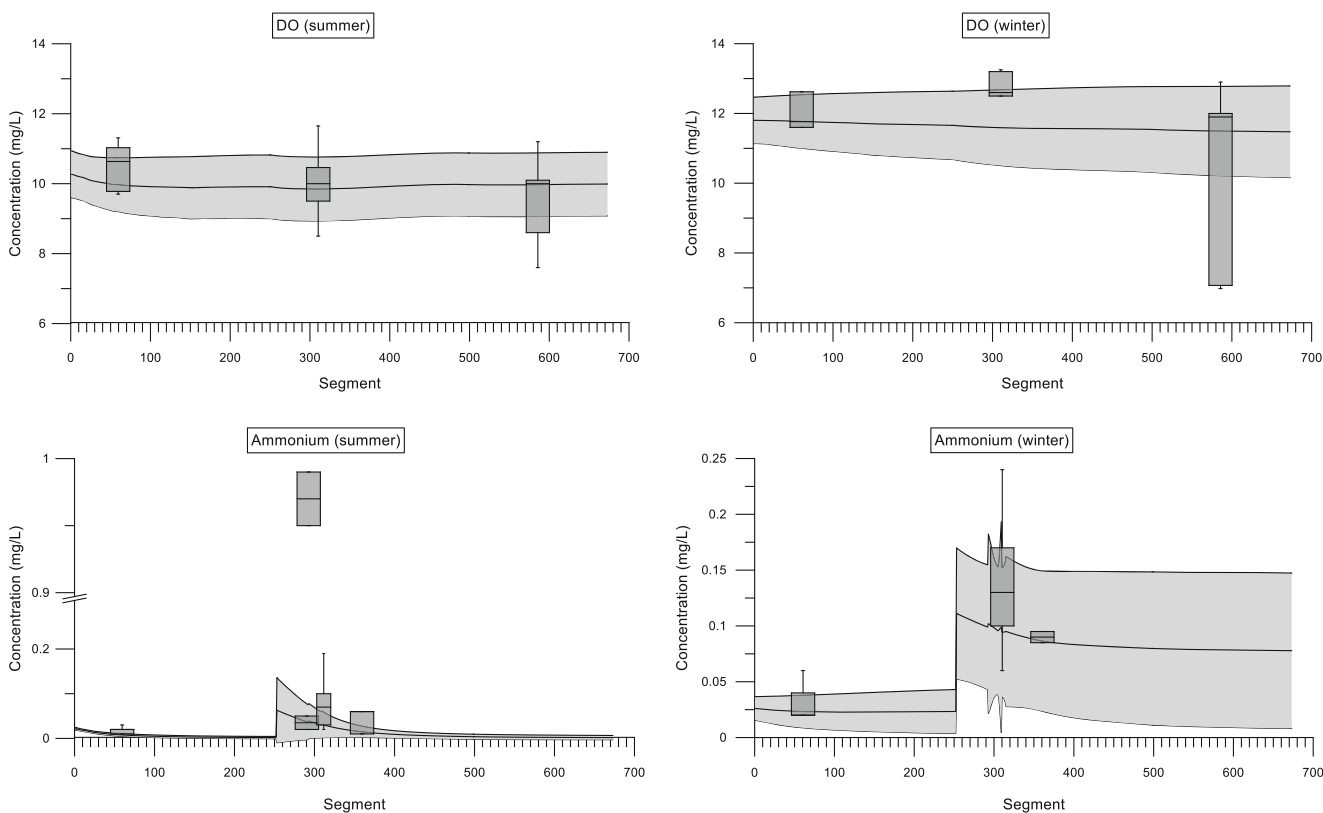

Fig. 11 Average dissolved oxygen and ammonium concentrations along the river. The upper and lower lines are [average + standard deviation] and [average − standard deviation], respectively, the middle line is average values, and the box plots summarise the observed data

simulation time period are summarised by the box-whisker plots. The model was capable of spatially capturing the DO and NH_4 concentrations in the simulation. A few outliers are present in the NH_4 sampled data at the downstream portion of the studied reach.

Overall, DO concentrations were higher during the ice-covered period than in the ice-free period. As mentioned by Prowse [8], although ice cover reduces the reaeration rate, which can lead to lower DO concentrations in the water column, this reduction may not lead to the annual minimum DO due to the lower amount of organic loading and lower water temperatures in winter. In the ice-free season, there was a DO sag downstream from the WWTP. The sag recovered as the water was reaerated. This recovery was not evident in winter due to restricted reaeration leading to a steady decrease in DO concentrations in the flow direction.

In the study by Diduck [26], the effluent from the Saskatoon WWTP is a major point source loading along the LSSR. In Fig. 11, the highest simulated NH_4 concentration peak occurs immediately downstream of the WWTP. Other smaller peaks in the simulated NH_4 concentrations occurred at lagoon effluents along the river. Very high NH_4

concentrations were observed downstream from the Martensville lagoon outfall, which was difficult to capture in the model simulations. The differences in the simulated and measured values may be due to the model's assumption that complete mixing of the effluent in the river water occurs immediately at the point of discharge. Diduck [26] stated that effluents from the Saskatoon WWTP (segment 244) do not completely mix in the surface water until Clarkboro Ferry (segment 310), a distance of 33 km. Hence, a mixing length should be taken into account when sampling is conducted. In addition, accurate loading values discharged from the effluent of lagoons and WWTPs could significantly improve the simulation results. For this study, point source loads from municipal effluents needed to be estimated. Monitoring concentrations and volumes at major point source loading at Outlook, Martensville and Warman could substantially reduce the uncertainty in the simulations.

The model performance was validated for the year 2011 using the calibrated parameters. Comparing the simulation results to the measured data yielded a correlation coefficient value of $r^2 = 0.67$. As an example of this comparison, Fig. 12 shows the simulated versus measured concentrations of DO at

Fig. 12 Simulated versus sampled concentrations of DO and NO_3
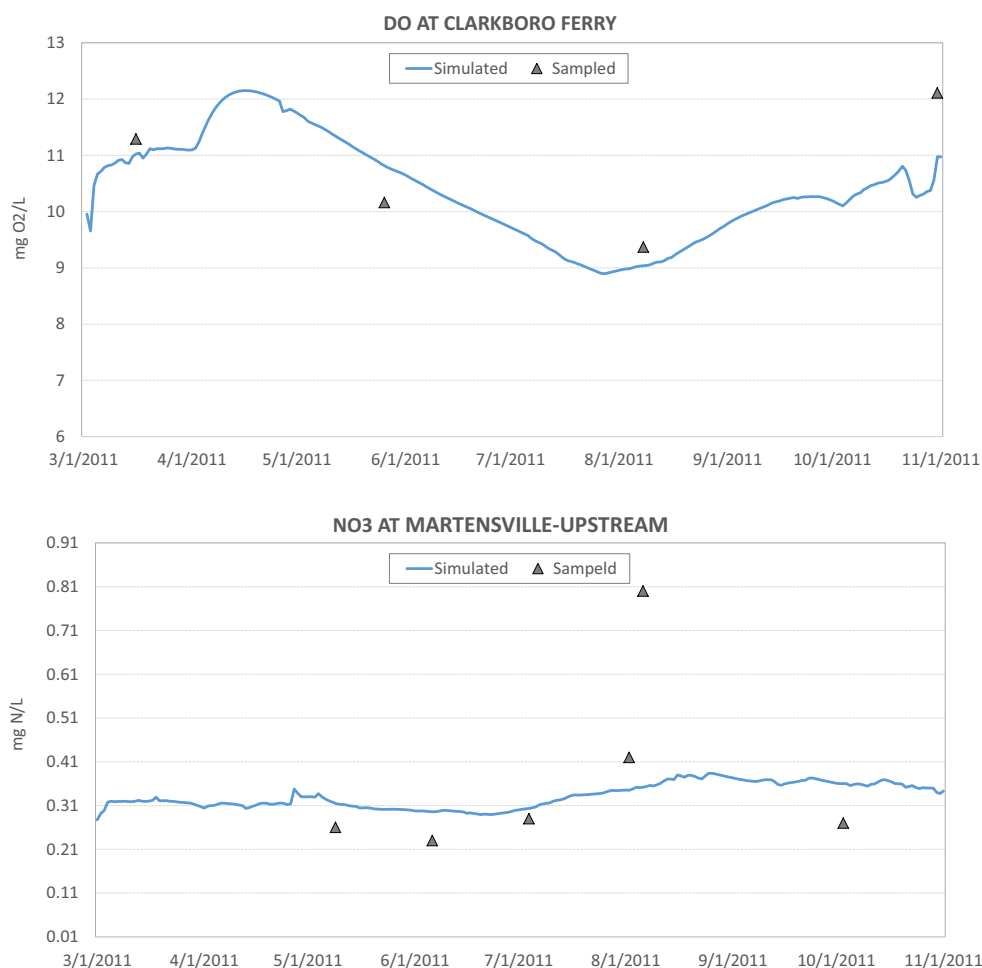
Clarkboro Ferry and nitrate (NO$_3$) at Martensville. The validation results show a relatively good fit between measured and corresponding simulated concentrations.

6.2 Sensitivity

The sensitivities of the simulated variables to identified parameters during the ice-free (May–October) and ice-covered (November–April) periods are provided in Fig. 13. These sensitivities are based on the root-mean-square error (RMSE) calculations using Eq. 1. The different levels of shading represent the degrees of impact of the parameter on each variable. The darker shading indicates that the parameter is more sensitive to the variable.

N-mineralisation (K71C and K71T) and nitrification (K12C and K12T) rates had the most influence on NH$_4$, and nitrification rates had a slight influence on NO$_3$. OPO$_4$ was slightly sensitive to phosphorus mineralisation (K83C and K83T). The parameters phosphorus mineralisation, nutrient/carbon ratio and faction of phytoplankton recycling related to phosphorus (K83C, PCRB and fOP) were particularly sensitive to OP. The phytoplankton growth and death rates (K1C

and K1D) had more impact on phosphorus than on nitrogen determinants.

In general, parameter sensitivities were relatively similar in both the ice-free and ice-covered periods with higher degrees of sensitivity under the ice-free condition. It is interesting to note, however, that many variables are sensitive in ice-covered conditions and even a few parameters had more impact on the variables during the ice-on state than ice-off state. For example, SOD had a greater impact on DO under ice, indicating the importance of exchange between the water column and the sediment bed under ice conditions. The sensitivity of OPO$_4$ and OP to K83T was higher in the ice-covered season than the ice-free season.

Chlorophyll a was highly sensitive to phytoplankton death and growth rates and carbon to chlorophyll a ratio (K1D, K1C and CCHL). It also showed sensitivity to fOP and KMPG1 in the ice-free period, suggesting that there is a higher interaction between phosphorus and chlorophyll a in the ice-free period.

Light and nutrients are the most important resources for phytoplankton growth. Phytoplankton growth is affected by the amount of light and the availability of the nutrients relative to each other. Figure 14 provides the simulated results of nutrient and light limitations during the 3-year study period. The
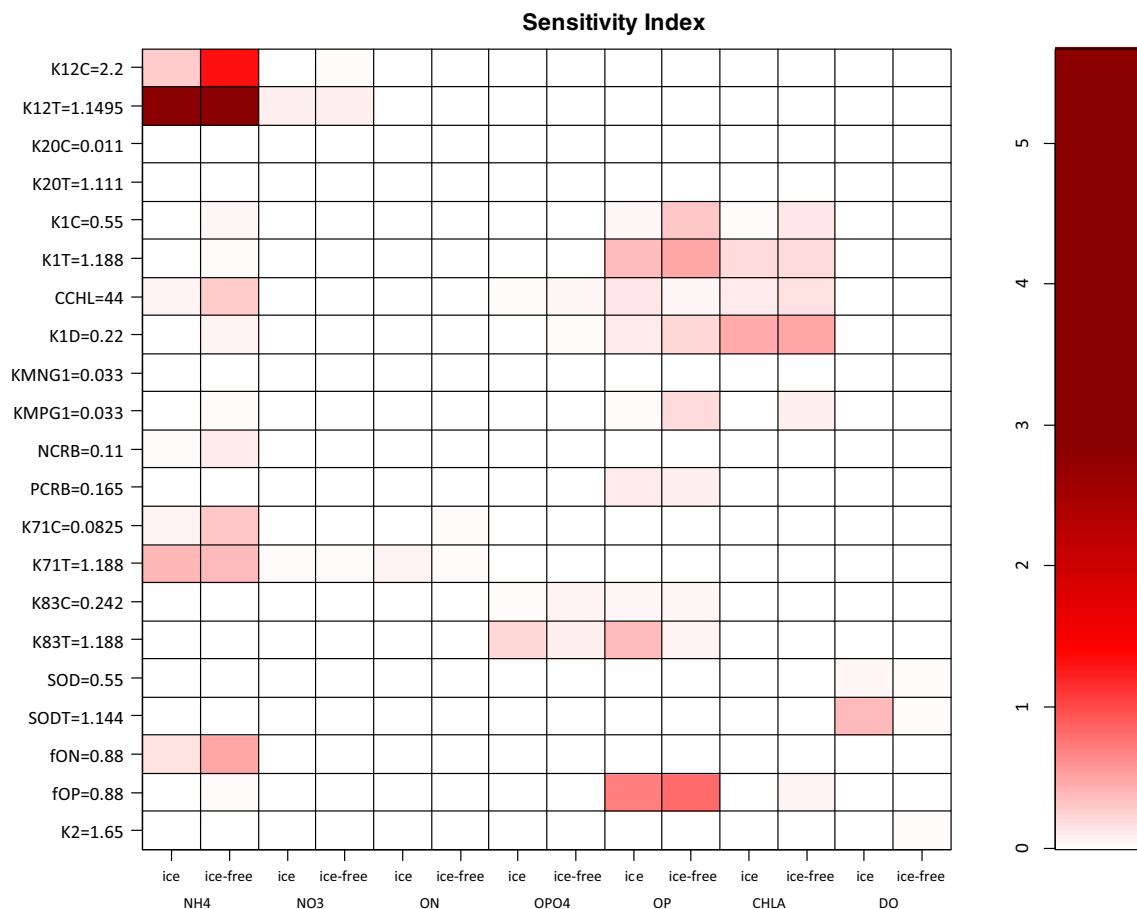

Fig. 13 Sensitivity analysis based on the ratio of difference in root-mean-squared errors to the parameter change (Eq. 1)
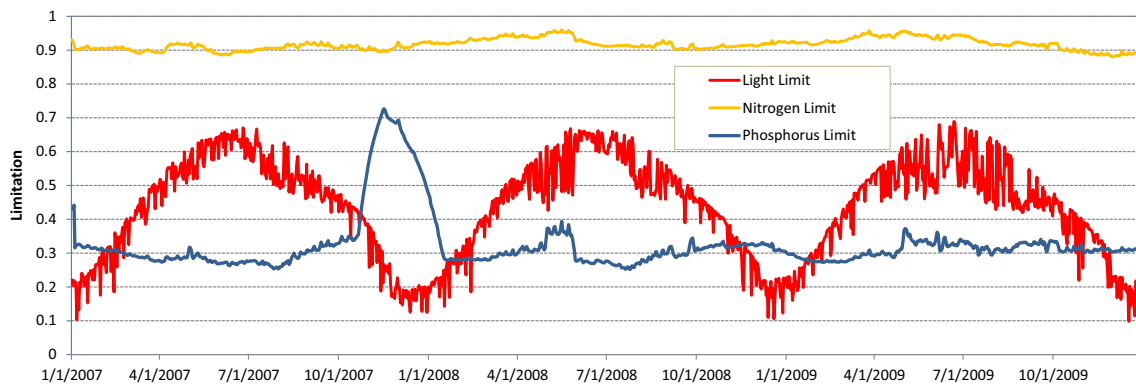
Fig. 14 Simulated nutrient and light limitation at Clarkboro Ferry during the 3-year studied time frame 2007–2009

limitation factor varies between 0 and 1, indicating complete limitation and no limitation, respectively. The results show that phosphorus is the limiting nutrient in the LSSR. Phosphorus limitation is expected because 90% of the phosphorus loading from the USSR is retained in Lake Diefenbaker, whereas the nitrogen budget shows no retention and even a slight enrichment as water flows through Lake Diefenbaker from the USSR into the LSSR. Note that phosphorus concentrations were commonly measured to be below the detection limit (<0.02 mg/l). A lower limit of detection and more accurate sampling could

significantly improve the model simulations. Figure 14 also shows that the system is overall light limited, which also contributes to parameters being less sensitive to phosphorus determinants under ice than in ice-free period.

6.3 Relative Entropy

Figure 15 shows the relative entropy between model responses driven by the base and perturbed parameters of seven water quality variables for both ice-covered and ice-free
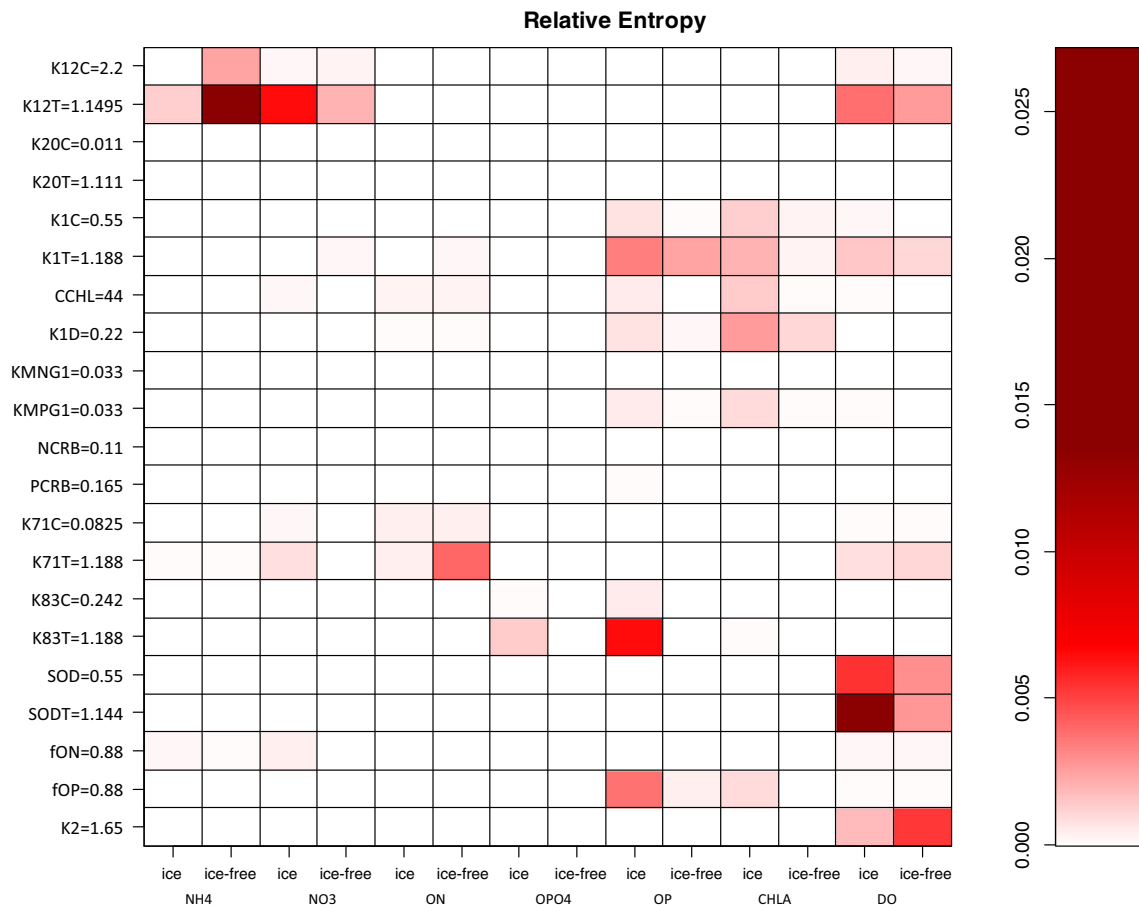

Fig. 15 Relative entropy

periods. Generally, the parameters which are sensitive for ice-free months are also sensitive for ice-covered months.

The relative entropies show similar patterns in parameter sensitivities to determinants as do the RMSE sensitivities, although for some, the relative magnitude of sensitivity is balanced differently so that some parameters are more sensitive, others less sensitive, to certain determinants. One important difference is the increased sensitivity of more parameters to DO, in particular the nitrification rate, reaeration rate and the N-mineralisation rate. Sediment oxygen demand parameters show more sensitivity to DO concentrations, particularly under ice.

Additionally, more parameters show slightly higher sensitivities in the ice-covered period compared to the ice-free period using relative entropy rather than RMSE sensitivities, especially to OP and Chl a. Again, growth, death and nutrient one-half-saturation rates were more sensitive to OP, than their nitrogen counterparts. In general, nitrification is an important process in the system.

As a result of the additive property of entropy, the sensitivity of the parameters for ice-on and ice-off conditions can be compared by the difference in their relative entropy (Fig. 16).

Among all the simulated variables, DO seems to be sensitive to most parameters. The reaeration rate, sediment oxygen demand and nitrification parameters (K2, SOD and K12C) appear to have different influences on DO in the ice-free and ice-covered months. The simulated ice-on and ice-off total nitrogen has different sensitivities to total nitrogen mineralisation (K71C). The response of ammonium and nitrate to the nitrification rate parameters (K12C and K12T) may be different between ice-covered and ice-free months.

Overall, the results of sensitivity indices and relative entropy are fairly consistent. Generally, phosphorus is more sensitive to parameters than nitrogen for both sensitivity indices. However, DO appears to be more sensitive in the entropy results. This may be due to the range of the DO RMSE in the order of 1 mg/l, which is an order of magnitude greater than the range for other variables typically in the order of 0.1 mg/l; the results stemming from Eq. 1 can be affected by the range of RMSE. For the Eq. 2 results, the computed entropy is not affected by the range of RMSE because it is based on probability. It appears that the entropy approach is able to give more salient sensitivity analysis results.

Fig. 16 Difference in relative entropy between ice-free and ice-covered periods
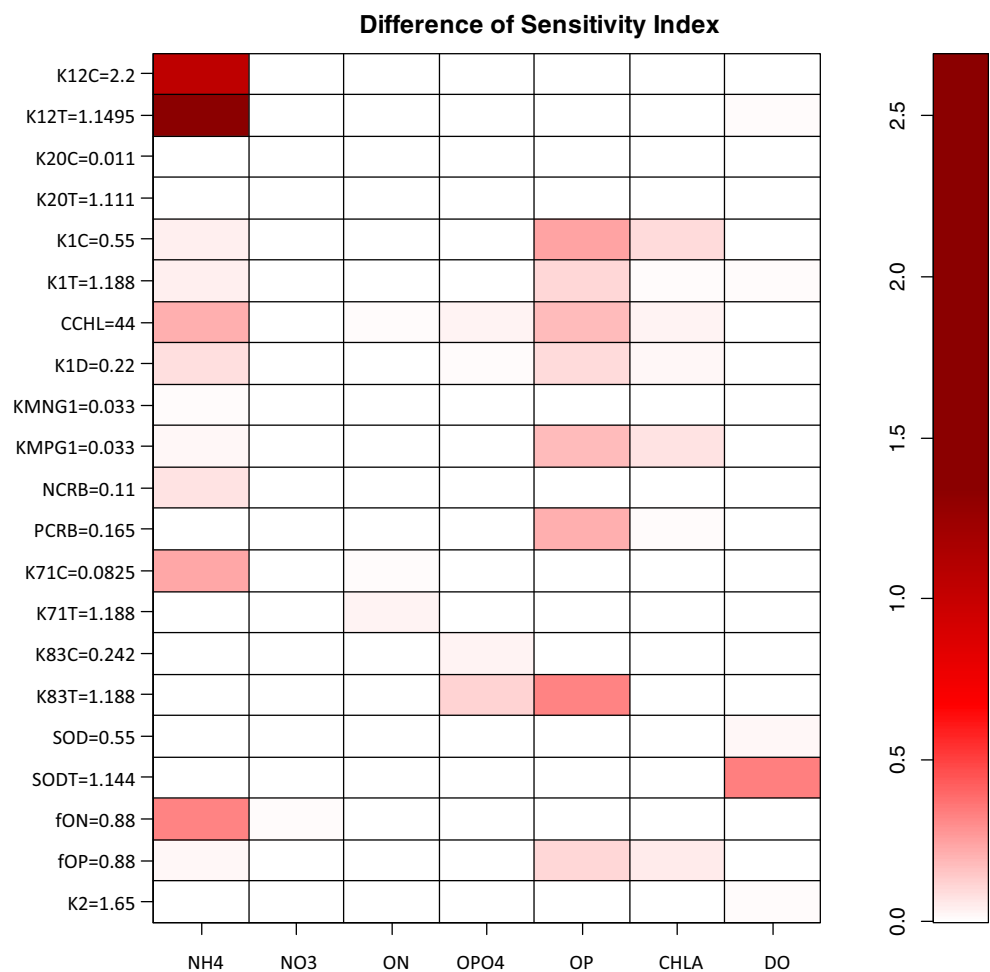
7 Limitations of the Model and Data

Uncertainty in model simulations can be due to different factors including lack of data, measurement errors and the coarseness of the spatial or temporal data resolution. Although there is a large set of available water quality data from government agencies, the data are usually sampled with a coarse temporal resolution. This coarse sampling cannot ensure accurate modelling of water quality for the entire simulation time period. To better simulate the water quality of the river and to best capture the changes in surface water quality along the river, high-frequency, continuous sampling through automated sampling stations would be beneficial. Such data would also be useful in differentiating between various processes affecting water quality [39] and in differentiating between hydrological inputs from the catchment area. Since boundary conditions have a great impact on model simulations, high-frequency sampling would be required mostly at the upstream boundary of the river. Real-time monitoring of surface water quality at Outlook or Lake Diefenbaker (from the hypolimnion and epilimnion layers of water) could significantly improve the model simulations of water quality along the river.

Measured macrophyte and periphyton (epilithic algae) were not available for the LSSR. Hence, our model simulation was set up for simulation and calibration against chlorophyll *a* as a representation of total algal biomass. This is a common practise (e.g. [40, 41]) and provides rational estimates of algal biomass [42]. Excessive macrophtyte growth was observed in the LSSR downstream of Saskatoon WWTP pre-1990 by several researches (e.g. [43–46]); however, based on the study by Constable [47], the macrophyte growth was very limited in 2000. Constable [47] states that

"This reduction in macrophyte is likely due to a coincidental scouring of the fine sediment by flood in 1991, 1992, and 1995, and the reduction in nutrients and TSS from sewage effluents in 1996."

Including future macrophyte survey would better represent the water quality of the system.

8 Conclusions

The Water Quality Analysis Simulation Program (WASP7) is well suited to studying the water quality of the LSSR. The LSSR was used as a case study; however, the approach can be adapted to other rivers in cold regions. Overall, the model is capable of predicting the water quality both spatially and temporally along the river. Since the travel time in the river is approximately 8 days, the model could be a useful tool for forecasting water quality in the downstream segments on the basis of observations at the upper segments. High-frequency

continuous sampling at the upper boundary segment could improve the model performance in predicting the water quality of the downstream segments.

A local sensitivity analysis was performed to study the sensitivity of parameters on water quality variables during both ice-on and ice-off periods. Surprising was to find that the sensitivity of some parameters was very high during the ice-covered period with some reaching sensitivity as high as that during the ice-free season. To check this unexpected result of high parameter sensitivities of water quality variables under ice, an independent approach using entropy was used to calculate parameter sensitivities. The relative entropies of each parameter showed a similar pattern to the local sensitivities determined from the RMSE calculations, substantiating our findings.

Phytoplankton growth parameters such as the growth, death and nutrient one-half-saturation rates had a greater influence on phosphorus, as compared to nitrogen, pointing to P-limitation in the system. The sensitivity analyses of the model parameters indicate that N-mineralisation and nitrification are the most sensitive parameters to nitrogen constituents. The sediment oxygen demand was the most sensitive parameter for the DO simulations with higher sensitivity under ice-covered conditions. In open-water conditions, DO was sensitive to reaeration rate. The results showed that phosphorus is the limiting nutrient during open-water conditions and its simulation had a great impact on the phytoplankton simulation.

Moreover, phytoplankton growth and death rates (K1C and K1D) were sensitive in the ice-covered period and a chlorophyll *a* peak was determined to have occurred during freeze-up of 2007. These results indicate that the river ecosystem is relatively active under ice and steered by different processes under ice-covered compared to open-water conditions. In summary, the sensitivity analysis framework implemented in this study provides new possibilities for modelling and monitoring cold region river water quality.

A trend analysis shows that the period of ice cover in the LSSR is becoming shorter; hence, climate change may have implications on future water quality of the river, a topic of future research.

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